

REPORT DOCUMENTATION PAGE			Form Approved OMB NO. 0704-0188		
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1. REPORT DATE (DD-MM-YYYY) 23-01-2012		2. REPORT TYPE Final Report		3. DATES COVERED (From - To) 1-May-2005 - 31-Dec-2010	
4. TITLE AND SUBTITLE Final Report: Quantum Imaging: New Methods and Applications			5a. CONTRACT NUMBER W911NF-05-1-0197		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER 611103		
6. AUTHORS Principal Investigator, Robert W. Boyd			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAMES AND ADDRESSES University of Rochester ORPA University of Rochester Rochester, NY 14627 -0000			8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211			10. SPONSOR/MONITOR'S ACRONYM(S) ARO		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S) 48091-PH-MUR.5		
12. DISTRIBUTION AVAILABILITY STATEMENT Approved for Public Release; Distribution Unlimited					
13. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.					
14. ABSTRACT This document reports the results obtained in a five-year research program aimed at developing new imaging methods based on the quantum statistical properties of light fields. Significant results obtained in the life of the program include (1) demonstration of ghost imaging of an object using reflected light, (2) demonstration of the ability to discriminate between two objects when illuminated by only a single photon, and (3) the use of entangled photons to achieve aberration correction for even-order aberrations. Other areas of significant progress include:					
15. SUBJECT TERMS image science, quantum optics, quantum imaging					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Robert Boyd
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU			19b. TELEPHONE NUMBER 585-275-2329

## Report Title

Final Report: Quantum Imaging: New Methods and Applications

### ABSTRACT

This document reports the results obtained in a five-year research program aimed at developing new imaging methods based on the quantum statistical properties of light fields. Significant results obtained in the life of the program include (1) demonstration of ghost imaging of an object using reflected light, (2) demonstration of the ability to discriminate between two objects when illuminated by only a single photon, and (3) the use of entangled photons to achieve aberration correction for even-order aberrations. Other areas of significant progress include: development of new sources of entangled photons, development of new single photon detectors, use of thermal light to mimic quantum fluctuations in certain imaging protocols, new theoretical approaches to optical coherence theory, quantum entanglement based on orbital angular momentum, use of ghost imaging for imaging through biological materials, exploiting the large information content of entangled images, use of quantum techniques to enhance the properties of optical coherence tomography, development of methods for quantum lithography, theoretical treatment of new methods for producing and utilizing N00N states, and theoretical development of efficient N-photon absorbers. This program has also had a large positive impact on the education of students. During the life of the award, we trained 17 PhD students and 5 postdoctoral fellows, who are an asset to the nation's workforce.

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**Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:**

**(a) Papers published in peer-reviewed journals (N/A for none)**

<u>Received</u>	<u>Paper</u>
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**TOTAL:**

**Number of Papers published in peer-reviewed journals:** 0.00

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**(b) Papers published in non-peer-reviewed journals (N/A for none)**

<u>Received</u>	<u>Paper</u>
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01/23/2012	4.00 . Papers and Publications, MuRI papers, (01 2012): 0. doi:
------------	--

**TOTAL:** 1

**Number of Papers published in non peer-reviewed journals:**

---

**(c) Presentations**

Boston University

1. A. V. Sergienko, C. Bonato, B. E. A. Saleh, S. Bonora, and P. Villoresi, "Aberration Cancellation in Quantum Interferometry," 3rd International conference of Quantum Information, ICQI 2008, Boston, Massachusetts (July 2008). (Invited)
2. T. B. Bahder, D. S. Simon, and V. Sergienko, "Effect of Dispersion on Fidelity of Quantum Interferometer," 3rd International conference of Quantum Information, ICQI 2008, Boston, Massachusetts (July 2008).
3. C. Bonato, O. Minaeva, V. Sergienko, B. E. A. Saleh, S. Bonora, and P. Villoresi "Spatial and Spectral Phase Control in Quantum Interferometry," QCCQI 2008 Quantum/Classical Control in Quantum Information, Otranto, Italy (September 2008).
4. A.V.Sergienko, "Entanglement in Quantum Communication: Dispersion Cancellation and Decoherence-Free Subspaces," SECOQC Quantum Network Demonstration Conference, Vienna, Austria (October 2008).
5. O. Minaeva, C. Bonato, B. E. A. Saleh, and A. V. Sergienko, "Odd- and Even-Order Dispersion Cancellation in Quantum Interferometry," Frontiers in Optics, 2008 OSA Annual Meeting, Rochester, NY (October 2008).
6. Sergienko, O. Minaeva, C. Bonato, B. E. A. Saleh, and Paolo Villoresi "Dispersion Cancellation and Manipulation in Quantum Interferometry," Frontiers in Optics, 2008 OSA Annual Meeting, Rochester, NY (October 2008). (Invited)
7. M. B. Nasr, D. P. Goode, N. Nguyen, G. Rong, L. Yang, B. M. Reinhard, B. E. A. Saleh, and M. C. Teich, "Quantum Optical Coherence Tomography of a Biological Sample," IEEE Lasers & Electro-Optics Society (LEOS) Annual Meeting, Newport Beach, CA (November 2008).
8. M. C. Teich, "Multi-Photon and Entangled-Photon Imaging and Lithography," Invited Lecture, Department of Physics and OSA Section, Humboldt University, Berlin, Germany and Max Born Institute, Berlin-Adlershof, Germany (November 2008). (Invited)
9. N. Mohan and M. C. Teich, "Ultra-Broadband Optical Coherence Tomography Using Parametric Downconversion and Superconducting Single-Photon Detectors at 1064 nm," Invited Presentation, The Bernard M. Gordon Center for Subsurface Sensing and Imaging Systems, Boston, Massachusetts (April 2009). (Invited)
10. O. Minaeva, A. Divochiy, A. Korneev, A. V. Sergienko, and G. N. Gol'tsman, "Number Resolving Superconducting Single-Photon High Speed Infrared Photon Counting with Photon Detectors (SSPDs)," CLEO/Europe-IQEC, 19th International Congress on Photonics in Europe, Munich, Germany (June 2009).
11. V. Sergienko, O. Minaeva, D. Simon, B. E. A. Saleh, and C. Bonato, "Quantum Dispersion Cancellation in Frequency and in Space," CLEO/Europe-IQEC, 19th International Congress on Photonics in Europe, Munich, Germany (June 2009).
12. M. C. Teich, "Multi-Photon and Entangled-Photon Imaging and Lithography," Invited Lecture, Eleventh International Conference on Squeezed States and Uncertainty Relations, Palacky University, Olomouc, Czech Republic (June 2009). (Invited)
13. M. C. Teich, "Multi-Photon and Entangled-Photon Imaging and Lithography," Physical Chemistry Seminar, Department of Chemistry, Boston University, Boston, Massachusetts (September 2009).
14. N. Mohan and M. C. Teich, "Photon-Counting Coherence-Domain Imaging in the 1- $\mu$ m Wavelength Range," Invited Poster, Research and Industrial Collaboration Conference (RICC), The Bernard M. Gordon Center for Subsurface Sensing and Imaging Systems, Boston, Massachusetts (October 2009).
15. M. F. Saleh, B. E. A. Saleh, and M. C. Teich, "Modal, Spectral, and Polarization Entanglement in Guided-Wave Parametric Down-Conversion," Frontiers in Optics 2009, Annual Meeting of the Optical Society of America, San Jose, California (October 2009).
16. M. C. Teich, A. V. Sergienko, and B. E. A. Saleh, "When Can Quantum Imaging Benefit from Entangled Photons," Invited Presentation, Army Research Office MURI Meeting, Evanston, Illinois (November 2009).
17. N. Mohan, A. V. Sergienko, O. Minaeva, G. N. Gol'tsman, M. B. Nasr, B. E. A. Saleh, and M. C. Teich, "Photon-Counting Optical Coherence Tomography Using Superconducting Single-Photon Detectors," Workshop on Single and Entangled Photons: Sources, Detectors, Components, and Applications, NIST Boulder, Colorado (November 2009).
18. N. Mohan, I. Stojanovic, W. C. Karl, B. E. A. Saleh, and M. C. Teich, "Compressed Sensing in Optical Coherence Tomography," SPIE BiOS: Biomedical Optics, SPIE Conference on Three-Dimensional and Multidimensional Microscopy: Image Acquisition and Processing XVII, SPIE Photonics West, San Francisco, California (January 2010).
19. M. C. Teich, "Multi-Photon and Entangled-Photon Imaging and Lithography," Invited Seminar, Electrical Engineering & Computer Science/Research Laboratory of Electronics Seminar Series on Optics and Quantum Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts (April 2010).
20. M. C. Teich, "Can Quantum Imaging Benefit from Entangled Photons?" Invited Talk, Annual Meeting of the MIT Center for Integrated Photonic Systems (CIPS), Massachusetts Institute of Technology, Cambridge, Massachusetts (June 2010).
21. M. C. Teich, "When Can Quantum Imaging Benefit from the Use of Entangled Photons?" SPIE Optics + Photonics Meeting: Quantum Communications and Quantum Imaging VIII, San Diego, California (August 2010).
22. V. Sergienko, N. Mohan, O. Minaeva, G. N. Goltsman, M. B. Nasr, B. Saleh, and M. C. Teich, "Superconducting Photon-Counting Detectors in Optical Measurement and Biophotonics Applications," SPIE Optics + Photonics Meeting: Single-Photon Imaging, San Diego, California (August 2010).
23. M. F. Saleh, G. Di Giuseppe, B. E. A. Saleh, and M. C. Teich, "Photonic Circuits for Quantum Information Processing in Two-Mode Integrated Diffused-Channel Waveguides," Frontiers in Optics 2010, Annual Meeting of the Optical Society of America, Rochester, New York (October 2010).

Louisiana State University

24. "Quantum Interferometric Sensing," Jonathan P. Dowling, Applied Atom Optics Conference, 27–29 July 2009, Bad Honnef, Germany (invited).
25. "Quantum Computing, Metrology, and Sensing," Jonathan P. Dowling, LPHYS09, 13–17 July 2009, Barcelona, Spain (invited).
26. "Quantum Computing, Metrology, and Sensing," Jonathan P. Dowling, US Government Quantum Technology Application Workshop, 30 June 2009, McLean, VA (invited).
27. "Quantum Computing, Metrology, and Sensing" Jonathan P. Dowling, SPIE Photonics West: Quantum Electronics Metrology, 25–30 January 2009, San Jose, California (invited).
28. "Quantum Technologies — The Second Quantum Revolution," Jonathan P. Dowling, US Army Emerging Technologies Seminar, 6–9 October 2008, McLean, Virginia (invited).
29. "Quantum Technologies — The Second Quantum Revolution," Jonathan P. Dowling, US Army Future Technology Seminar, 19–21 August 2008, Portsmouth, Virginia (invited).
30. Hwang Lee, Yang Gao, A Simple Criterion for Quantum States of Light to Be Applicable for the Heisenberg-Limited Interferometry, 40th Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics, May 19–23, 2009; Charlottesville, VA.
31. Aravind Chiruvelli, Hwang Lee, Parity Detection in Quantum Optical Metrology, 40th Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics, May 19–23, 2009; Charlottesville, VA.
32. Sulakshana Thanvanthri, Kishore T. Kapale, Jonathan P. Dowling, Ultra stable Matter wave gyroscopy using Orbital Angular Momentum induces atomic vortices, 40th Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics, May 19–23, 2009; Charlottesville, VA.
33. Blane McCracken, Tae-Woo Lee, Sean D. Huver, Lev Kaplan, Hwang Lee, Changjun Min, Dmitry B. Uskov, Christoph F. Wildfeuer, Georgios Veronis, Jonathan P. Dowling, Optimization of States in a Lossy Interferometer, 40th Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics, May 19–23, 2009; Charlottesville, VA.
34. Christoph Wildfeuer, Aaron Pearlman, Jun Chen, Jingyun Fan, Alan Migdall, Jonathan Dowling, Interferometry with a photon-number resolving detector, 40th Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics, May 19–23, 2009; Charlottesville, VA.
35. Petr Anisimov, William N. Plick, Christoph F. Wildfeuer, Hwang Lee, Jonathan P. Dowling, Two-photon absorption of path-entangled number states, 40th Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics, May 19–23, 2009; Charlottesville, VA.
36. Hwang Lee, "Heisenberg-Limited Optical Interferometry: A Universal Detection Scheme," 17th International Laser Physics Workshops, Trondheim, Norway (June 30–July 4, 2008)
37. Aravind Chiruvelli, Yang Gao, and Hwang Lee, "A Universal Detection Scheme for Sub-Shot Noise Interferometry," Optical Society of America, Annual Meeting/Laser Science XXIV, Rochester, NY (October 19–23, 2008).
38. Hwang Lee, "Density Matrix Formalism for Heisenberg-Limited Interferometry" SPIE Photonics West 2009, San Jose, CA (January 24–29, 2009).
39. "Optimization of Linear Optical Quantum Computing Circuits," Jonathan P. Dowling, SPIE Photonics West: Advances in Photonics of Quantum Computing, Memory, and Communication III, 23–28 January 2010, San Jose, California (invited).
40. "Quantum Tripwire," Petr M. Anisimov, Blane McCracken, Daniel Lum, Jonathan P. Dowling, SPIE Photonics West: Advances in Photonics of Quantum Computing, Memory, and Communication III, 23–28 January 2010, San Jose, California.
41. "Entanglement-Boosted Bright-Source Interferometry," William N. Plick, Petr M. Anisimov, Jonathan P. Dowling, SPIE Photonics West: Advances in Photonics of Quantum Computing, Memory, and Communication III, 23–28 January 2010, San Jose, California.
42. "Optimization of States in a Lossy Interferometer," Blane McCracken, Tae-Woo Lee, Sean D. Huver, Lev Kaplan, Hwang Lee, Chang-Jun Min, Dmitry B. Uskov, Christoph F. Wildfeuer, Georgios Vero-nis, Jonathan P. Dowling, Single Photon Workshop, 3–6 November 2009, Boulder, Colorado.
43. "Sub-Heisenberg limited phase measurement with two-mode squeezed light," Petr M. Anisimov, Gretchen M. Raterman, Aravind Chiruvelli, William N. Plick, Sean D. Huver, Hwang Lee, Jonathan P. Dowling, Single Photon Workshop, 3–6 November 2009, Boulder, Colorado.
44. "The Quantum Tripwire: Analysis in the Presence of Photon Loss," Daniel J. Lum, S. Blane McCracken, Petr M. Anisimov, Jonathan P. Dowling Jonathan P. Dowling, Single Photon Workshop, 3–6 November 2009, Boulder, Colorado.

University of Maryland, Baltimore County – None

Massachusetts Institute of Technology

45. 28. B. I. Erkmen and J. H. Shapiro, "Unified theory of classical and quantum ghost imaging," presented at Physics of Quantum Electronics 2009, Snowbird, UT, January 2009.

University of Rochester

46. Robert W. Boyd: departmental colloquium presented at Los Alamos National Laboratory.
47. Robert W. Boyd: departmental colloquium presented at the University of New Mexico.
48. Robert W. Boyd: departmental colloquium presented at the University of Erlangen.
49. Robert W. Boyd: departmental colloquium presented at the Danish Technical University.
50. Robert W. Boyd: invited talk at the international conference PQE, Snowbird Utah.
51. Robert W. Boyd: invited talk at the international conference SPIE DSS, Orlando.
52. Robert W. Boyd: invited talk at the international conference OASIS (an Israeli conference somewhat similar to CLEO), Tel Aviv.
53. Robert W. Boyd: invited talk at the international conference Photonics West, San Jose.
54. Robert W. Boyd: invited talk at the international conference ICSSUR, Olomouc, Czech Republic
55. Robert W. Boyd: invited talk at the international conference SPIE Annual Meeting, San Diego, CA
56. Robert W. Boyd: invited talk at the international conference ICSSURS, Olomouc, Czech Republic.
57. 40. Robert W. Boyd: invited talk at the international conference Optical Society of America Annual Meeting, Rochester, NY
58. 41. Robert W. Boyd: oral presentation at the international conference IQEC, Baltimore, MD.
59. Robert W. Boyd: oral presentation at the international conference Nonlinear Optics (an OSA conference)
60. John Howell, Stanford SPRC Annual Symposium, (Sept 2009) (Invited)
61. John Howell, OSA Topical Meeting for Slow Light, Honolulu (July 2009)
62. John Howell, 2009 CLEO/QELS Meeting (May 2009) (Invited)
63. John Howell, Tel Aviv University Symposium, (March 2009) (Invited)
64. John Howell, Oasis 2, Israel, (March 2009)(Invited)
65. John Howell, Ithaca College Colloquium (April 2009) (Invited),
66. John Howell, Air Force Institute of Technology Colloquium (Feb 2009 ) (Invited)
67. John Howell, Physics of Quantum Electronics 2009 (Jan 2009) (Invited)
68. John Howell, LEOS East Symposium Speaker (Oct 2008) (Invited)
69. John Howell, OSA Frontiers in Optics (Oct 2008) (Invited)

**Number of Presentations:** 69.00

**Non Peer-Reviewed Conference Proceeding publications (other than abstracts):**

<u>Received</u>	<u>Paper</u>
12/09/2011	3.00 Multiple authors. Quantum Imaging: New Methods and Applications, Multiple. 2011/12/21 00:00:00, . : ,
<b>TOTAL:</b>	<b>1</b>

**Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):**

**Peer-Reviewed Conference Proceeding publications (other than abstracts):**

<u>Received</u>	<u>Paper</u>
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**TOTAL:**

(d) Manuscripts

<u>Received</u>	<u>Paper</u>
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TOTAL:

Number of Manuscripts:

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Books

<u>Received</u>	<u>Paper</u>
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12/09/2011	1.00 Robert W. Boyd. Nonlinear Optics, New York: Academic Press, (01 2008)
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TOTAL: 1

Patents Submitted

“Photonic-crystal architecture for frequency- and angle-selective thermal emitters,” M. Florescu, H. Lee, and J. P. Dowling, patent pending.

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“Phase-conjugate optical coherence tomography methods and apparatus,” B.I. Erkmen and J. Shapiro; patent pending.

Patents Awarded

“High-flux entangled photon generation via parametric processes in a laser cavity,” M.C. Teich, B.E.A. Saleh, A.V. Sergienko, J.T. Fourkas, R. Wolleschensky, M. Kempe, and M.C. Booth; U.S. Patent Number 6,982,822, issued January 3, 2006.

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“Efficient room temperature source of polarized single-photons,” S.G. Lukishova, R.W. Boyd, and C. R. Stroud, U.S. Patent Number 7,253,871, issued August 7, 2007.

Awards

-M. C. Teich, "Fractal Point Events in Physics, Biology, and Communication Networks," Boston University College of Engineering

Distinguished Lectureship, Boston, Massachusetts (March 2009).

Louisiana State University

-Dr. Jonathan Dowling was elected a Fellow of American Physical Society in Fall 2008.

-Dr. Jonathan Dowling was elected Fellow of the AAAS.

-Dr. Jeffrey Shapiro received the 2008 Quantum Communication Award for Theoretical Research. It was presented at the Ninth

International Conference on Quantum Communication, Measurement and Computing, in Calgary, Canada, August 2008.

The citation read

"for seminal contributions to the communication theory of systems with quantum effects."

-Dr. Jeffrey Shapiro received an Outstanding Referee Award from the American Physical Society.

-P. Kumar received Distinguished Lecturer Award from the IEEE Photonics Society

-P. Kumar was elected a Fellow of the American Association for the Advancement of Science (AAAS)

-Robert Boyd is the 2009 recipient of the Willis E. Lamb Award for Laser Science and Quantum Optics.

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### Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	<u>Discipline</u>
Venkatraman, Dheera	0.16	
Dolgaleva, Ksenia	1.00	
Jha, Anand	0.75	
Malik, Mehul	0.00	
O'Sullivan, Colin	0.75	
Shin, Heedeuk	1.00	
Zerom, Petros	1.00	
Gao, Yang	1.00	
Jiang, Kebei	1.00	
Chen, H.	0.50	
Kamaker, S.	0.50	
Liu, J.B.	0.50	
Tamma, V.	0.50	
Yu, Z.	1.00	
Broadbent, Curtis	0.88	
Armstrong, Gregory	0.45	
Mohan, Mishant	0.50	
Simon, David	0.50	
Minaeva, Olga	0.00	
Bonato, Cristian	0.00	
Saleh, Mohammed	0.00	
Chen, Chao-Hsiang	0.50	
Whitehead, Thomas	0.75	
Hardy, Nicholas	0.80	
Mouradian, Sara	0.20	
Gao, Boshen	1.00	
Dixon, Paul	1.00	
Howland, Gregory	1.00	
Gehring, George	0.50	
<b>FTE Equivalent:</b>	<b>17.74</b>	
<b>Total Number:</b>	<b>29</b>	

### Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
Le Gouet, Julien	0.08
Nasr, Magued B.	0.00
DeGiusseppe, Giovanni	0.00
Anisimov, P.	1.00
Feng, Sheng	0.50
<b>FTE Equivalent:</b>	<b>1.58</b>
<b>Total Number:</b>	<b>5</b>

### Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	National Academy Member
Teich, Malvin C.	0.11	
Boyd, Robert	0.11	
Shapiro, Jeffrey H.	0.08	
Saleh, Bahaa E. A.	0.11	
Sergienko, Alexander V.	0.11	
Reinhard, Bjorn M.	0.00	
Dowling, Jonathan	0.16	
Lee, Hwang	0.16	
Shih, Y. H.	0.08	
Rubin, M. H.	0.08	
Howell, John C.	0.12	
Barbosa, Geraldo	0.25	
Kumar, Prem	0.10	
<b>FTE Equivalent:</b>	<b>1.47</b>	
<b>Total Number:</b>	<b>13</b>	

### Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	Discipline
Samolis, Christos	0.25	
Wills, Peter	0.00	REU Fellow, Summer 2009
Lum, Daniel	0.00	REU Fellow, Summer 2009
Corseti, James	0.00	Intern, Summer 2009
Martuscello, Karen	0.00	Xerox Undergrad Research Fellow, Summer 2010
Krogstad, Molly	0.00	REU Fellow, Summer 2010
<b>FTE Equivalent:</b>	<b>0.25</b>	
<b>Total Number:</b>	<b>6</b>	



### Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: .....	7.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:.....	7.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:.....	7.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):.....	7.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:.....	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense .....	2.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: .....	0.00

### Names of Personnel receiving masters degrees

#### NAME

Simon, David

**Total Number:** 1

### Names of personnel receiving PhDs

#### NAME

Gehring, George

Shin, Heedeuk

Jha, Anand

Dolgaleva, Ksenia

Mohan, Nishant

Saleh, Mohammed

Simon, David

Glasser, Ryan

Plick, Wiliam

**Total Number:** 9

### Names of other research staff

#### NAME

Wang, Franco

Li, Xiaoying

Schnitzler, Maria

**FTE Equivalent:** 0.60

**Total Number:** 3

### Sub Contractors (DD882)

1 a. University of Maryland Baltimore County

1 b. Senior Grants and Contracts Manager

Office of Sponsored Programs

Baltimore MD 21250

**Sub Contractor Numbers (c):**

**Patent Clause Number (d-1):**

**Patent Date (d-2):**

**Work Description (e):**

**Sub Contract Award Date (f-1):**

**Sub Contract Est Completion Date(f-2):**

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1 a. Massachusetts Institute of Technology

1 b. 77 Massachusetts Avenue

Cambridge MA 021394307

**Sub Contractor Numbers (c):**

**Patent Clause Number (d-1):**

**Patent Date (d-2):**

**Work Description (e):**

**Sub Contract Award Date (f-1):**

**Sub Contract Est Completion Date(f-2):**

---

1 a. Massachusetts Institute of Technology

1 b. 77 Massachusetts Avenue

Cambridge MA 021394307

**Sub Contractor Numbers (c):**

**Patent Clause Number (d-1):**

**Patent Date (d-2):**

**Work Description (e):**

**Sub Contract Award Date (f-1):**

**Sub Contract Est Completion Date(f-2):**

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1 a. Northwestern University Evanston Campus

1 b. Office for Sponsored Research (OSR)

1801 Maple Ave., Suite 2410

Evanston IL 60201

**Sub Contractor Numbers (c):**

**Patent Clause Number (d-1):**

**Patent Date (d-2):**

**Work Description (e):**

**Sub Contract Award Date (f-1):**

**Sub Contract Est Completion Date(f-2):**

---

1 a. Northwestern University Evanston Campus

1 b. Research and Sponsored Programs

633 Clark Street

Evanston IL 602081110

**Sub Contractor Numbers (c):**

**Patent Clause Number (d-1):**

**Patent Date (d-2):**

**Work Description (e):**

**Sub Contract Award Date (f-1):**

**Sub Contract Est Completion Date(f-2):**

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1 a. Boston University

1 b. Office of Sponsored Programs

Trustees of Boston University

Boston MA 02215

**Sub Contractor Numbers (c):**

**Patent Clause Number (d-1):**

**Patent Date (d-2):**

**Work Description (e):**

**Sub Contract Award Date (f-1):**

**Sub Contract Est Completion Date(f-2):**

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1 a. Boston University

1 b. 881 Commonwealth Avenue

Boston MA 022151303

**Sub Contractor Numbers (c):**

**Patent Clause Number (d-1):**

**Patent Date (d-2):**

**Work Description (e):**

**Sub Contract Award Date (f-1):**

**Sub Contract Est Completion Date(f-2):**

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1 a. Louisiana State University

1 b. Office of Accounting Services

Sponsored Program Accounting

Baton Rouge LA 70803

**Sub Contractor Numbers (c):**

**Patent Clause Number (d-1):**

**Patent Date (d-2):**

**Work Description (e):**

**Sub Contract Award Date (f-1):**

**Sub Contract Est Completion Date(f-2):**

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**Inventions (DD882)**

5    **“Efficient room temperature source of polarized single-photons,”**

Patent Filed in US? (5d-1)     Y

Patent Filed in Foreign Countries? (5d-2)     N

Was the assignment forwarded to the contracting officer? (5e)     N

Foreign Countries of application (5g-2):

5a: S.G. Lukishova, R.W. Boyd, and C. R. Stroud

5f-1a: University of Rochester

5f-c:

5    **“High-flux entangled photon generation via parametric processes in a laser cavity,”**

Patent Filed in US? (5d-1)     Y

Patent Filed in Foreign Countries? (5d-2)     N

Was the assignment forwarded to the contracting officer? (5e)     Y

Foreign Countries of application (5g-2):

5a: M.C. Teich, B.E.A. Saleh, A.V. Sergienko, J.T. Fourkas, R. W

5f-1a: Boston University

5f-c:

5    **“Phase-conjugate optical coherence tomography methods and apparatus,” B**

Patent Filed in US? (5d-1)     N

Patent Filed in Foreign Countries? (5d-2)     N

Was the assignment forwarded to the contracting officer? (5e)     N

Foreign Countries of application (5g-2):

5a: B.I. Erkmén and J. Shapiro

5f-1a: Massachusetts Institute of Technology

5f-c:

5    **“Photonic-crystal architecture for frequency- and angle-selective thermal emitters,”**

Patent Filed in US? (5d-1)     N

Patent Filed in Foreign Countries? (5d-2)     N

Was the assignment forwarded to the contracting officer? (5e)     N

Foreign Countries of application (5g-2):

5a: M. Florescu, H. Lee, and J. P. Dowling

5f-1a: Louisiana State University

5f-c:

**Scientific Progress**

**Technology Transfer**

## **Scientific Narrative**

### **Introduction**

Recent advances in quantum optics and in quantum information science have opened the possibility of entirely new methods for forming optical images with unprecedented sensitivity and resolution. This new field of research, known as quantum imaging, has led to other breakthroughs as well, such as the possibility of imaging without interaction, with enormous implications for realistic real-world problems. Significant research has been performed over the past decade that is aimed at addressing these issues and at developing new methods of image formation based on the concept of quantum imaging. Quantum imaging implements ideas and techniques from the fields of quantum optics and nonlinear optics. In addition, quantum imaging offers significant opportunities within the broader field of quantum information science because the parallelism intrinsic to image-bearing beams leads to increased information capacity.

Four specific imaging modalities have been studied over the course of our research project. These modalities were chosen to be representative of the field of quantum imaging and to have specific relevance to DoD needs. These systems are: (1) Optical coherence tomography, in which quantum effects can be used to increase the axial resolution of the imaging system and to extract useful information regarding the dispersion of the material. (2) Ghost imaging, in which one can use coincidence techniques to form images using photons that have never interacted with the object to be imaged, (3) Laser radar, for which the use of a noise-free quantum preamplifier can increase the sensitivity of detection, and (4) Quantum lithography, for which quantum-entangled photons can be used to write structures at a resolution exceeding that imposed by classical diffraction theory.

In order to achieve these goals, new technologies have been developed. Examples of technologies that have played a key role in the development of quantum imaging include the creation of intense sources of entangled photons based upon (1) guided-wave interactions in periodically poled materials, (2) third-order interactions in atomic vapors, and (3) on the orbital angular momentum of light beams. Also important is the development of means of producing high-order entanglement, both in the sense of two-photon entanglement in a large Hilbert space of pixels and in the sense of entanglement of more than two photons. Both experimental and theoretical studies of these issues have been conducted.

Many of the key results of this program have been published as review articles in a special issue of the journal *Quantum Image Processing*. Details can be found there. This special issue consists of four review articles that span many of the topics of current interest in the field of quantum imaging. Teich, Saleh, Wong, and Shapiro present a review of the field of quantum optical coherence tomography (OCT). Howell, Anisimov, Dowling, Boyd present a review of imaging modalities based on the use of individual (or a small number of) photons and biphotons and a review of high-dimensional quantum communication. Shapiro, and Boyd present a review of the physics of ghost imaging. Finally, Boyd and Dowling present a review of the field of ghost imaging, including the choice of material systems for its implementation.

In this Final Report we present a summary of the key results of our research efforts.

### **Quantum Laser Radar**

This topic was pursued by Prem Kumar of Northwestern University and Jeffrey H. Shapiro of the Massachusetts Institute of Technology. The objective of the quantum laser radar work was to evaluate and develop quantum-imaging techniques specifically suited to improving the

sensitivity and spatial resolution of laser radars. In particular, they proposed to employ spatially broadband phase-sensitive amplification as a noiseless pre-amplifier for one quadrature of the target-return image field. Because typical laser-radar targets have surfaces that are quite rough on the scale of the illumination wavelength, they produce quasi-Lambertian reflections that exhibit fully-developed laser speckle. The challenge, therefore, in exploiting phase-sensitive amplification for laser radar applications is to derive a suitable phase reference to determine the single quadrature to be amplified and detected. In prior work at Northwestern University, a corresponding time-domain problem had been solved — in the context of fiber-optic communication — through a double-sideband suppressed carrier technique. The research plan for experiments was to develop the spatially-broadband amplifier and try to derive the necessary phase reference from the on-axis return in the image plane. Accompanying the Northwestern experimental effort was theoretical work at MIT. Previous work there had established system theory results for coherent laser radars using heterodyne detection to image both specular and rough-surfaced targets.

During the course of the MURI program substantial progress was made at Northwestern University on technology for spatially broadband phase-sensitive amplification. Building on previous work that had shown the feasibility of noise-free image amplification — although with limited achievable phase-sensitive gains in those experiments — a flexible system was developed to overcome the gain limitations with use of much-higher-nonlinearity, periodically-poled 2nd-order nonlinear crystals (lithium niobate and potassium titanyl phosphate) together with off-the-shelf high-power optical amplifier technology that had become available in the telecom band. Gains larger than 10 dB over spatial bandwidths as high as 10 lines-pairs/mm could be obtained. Table-top proof-of-concept experiments in which optical phases between the pump, signal, and the local-oscillator beams could be easily stabilized, confirmed the advantage of using a phase-sensitive optical amplifier in surpassing the sensitivity and resolution degradation occurring with less-than-unity quantum efficiency detection. In concert with that experimental effort, the MIT work addressed the feasibility of deriving the necessary phase reference from the on-axis image plane light. Unfortunately, that analysis indicated that each diffraction-limited field of view was apt to have a phase that was statistically independent of the rest. As a result, the fundamental premise of this form of quantum laser radar was negated. Nevertheless, the Northwestern and MIT team members found a different concept for using phase-sensitive amplification, in conjunction with squeezed-vacuum injection to enhance the spatial resolution of a soft-aperture homodyne-detection laser radar. That concept was subsequently funded by DARPA under its Quantum Sensors Program as the central focus for a team led by Harris Communication Systems that, in addition to Northwestern and MIT, included participation from BBN and the University of Texas at Arlington. The Harris team met its Phase I goals and is now engaged in a Phase II program.

### **Ghost Imaging**

This topic was pursued by Robert Boyd of the University of Rochester, Jeffrey Shapiro of MIT, and Yanhua Shih of the University of Maryland Baltimore County. Ghost images are obtained by correlating the output of a single-pixel (bucket) photodetector—which collects light that has been transmitted through or reflected from an object—with the output from a high spatial-resolution scanning photodetector or photodetector array whose illumination has not interacted with that object. The term “ghost image” is apt because neither detector’s output alone can yield an image: the bucket detector has no spatial resolution, while the high spatial-

resolution detector has not viewed the object. The first ghost imaging experiment relied on the entangled signal and idler outputs from a spontaneous parametric downconverter, and hence the image was interpreted as a quantum phenomenon. Subsequent theory and experiments showed, however, that classical correlations can be used to form ghost images. For example, ghost images can be formed with pseudothermal light—for which quantum mechanics is not required to characterize its photodetection statistics. Our MURI team made a careful study of the physics underlying the process of ghost imaging. This work was specifically aimed at clarifying and uniting two disparate interpretations of pseudothermal ghost imaging, viz., two-photon interference versus classical intensity-fluctuation correlations. The team was also quite interested in studies of ghost imaging in reflection, ghost imaging through atmospheric turbulence, computational ghost imaging, and two-color ghost imaging.

### **Single-Photon Imaging**

This work was conducted by John Howell and Robert Boyd of the University of Rochester and Jon Dowling of LSU. Quantum information science has made great strides over the last two decades. Motivated by technologies that cannot be replicated classically, such as provably secure communication and factoring large numbers into their primes with the use of quantum computers there has been great interest in determining those systems where there is a “quantum advantage”. Researchers in the field of quantum imaging have sought to determine those advantages for imaging (see for example the review by Kolobov ). While the field of quantum imaging has many subfields, the work of our MURI team focused on imaging with single photons or biphotons. Further, the high information capacity of the single and biphotons was shown to be useful in increasing the information capacity of a quantum key distribution system. “Single photon imaging” almost sounds like an oxymoron. How can a single photon carry an image and even if it can, how can it be measured? Quantization of the electromagnetic field shows that the elementary unit of energy, “the photon,” can have infinite information capacity at zero temperature (no thermal noise photons). However, for fundamental and practical reasons, the amount of information that can be extracted from the photon has usually been limited to much less than a bit. From a fundamental perspective, the space-time modes of the quantization are not usually related to the space-time characteristics of a detector used to measure the photons. For example, the plane-wave decomposition of the field is a useful mathematical construct, but it not possible to measure. However, if one possessed a detector that could detect all plane-wave modes, the photon, even if it occupied all modes, would only be measured in a single eigenmode of that detector. It would then require an ensemble of identical photons to determine a single photon’s state. The implication is that an infinite number of photons are needed to determine the image written on the photon. We see then that we must use nonstandard methods for determining single photon images, as well we must ascertain the advantages of single photon imaging versus traditional classical methods.

### **Quantum Lithography**

This work was conducted by Robert Boyd of UR and Jonathan Dowling of LSU. As part of their MURI work, they provided an analysis of progress in the field of quantum lithography. They studied the conceptual foundations of this idea and the status of research aimed at implementing this idea in the laboratory. The selection of a highly sensitive recording material that functions by means of multiphoton absorption seems crucial to the success of the proposal of quantum lithography. Their work thus placed considerable attention on these materials



considerations. Quantum lithography is a technique first proposed by Boto et al. that allows one to write interference fringes with a spacing  $N$ -times smaller than the classical Rayleigh limit of resolution, which is approximately  $\lambda/2$ . The basic idea of quantum lithography can be understood from the simplest possible case, that of  $N = 2$ . A laser beam is allowed to fall onto a nonlinear mixing crystal in which parametric downconversion occurs, producing two daughter photons each at twice the wavelength of the pump laser beam. This photon pair then falls onto a 50-50 beam splitter. The output of the interferometer under these circumstances is the entangled state  $2,0 + 0,2$ , where the notation is such that  $n,m$  denotes a state in which  $n$  photons are in the upper output port of the beamsplitter and  $m$  photons are in the lower port [2]. Note that, as a consequence of quantum interference, one never finds one photon in each output port. These two output beams then interfere on a recording medium that responds by means of two-photon absorption. Fringes are formed by means of the interference between the probability amplitudes for two-photon absorption with the photon pair taking either the upper or the lower pathway. Each of these probability amplitudes depends on path length  $L$  as  $\exp(2ikL)$ , where the factor of 2 occurs because each of the two photons acquires the phase shift  $kL$ . The fringe spacing is thus twice as fine as that given by the normal interference patterns between the two waves. In many ways, the enhanced resolution can be understood from the point of view that the deBroglie wavelength of a quantum state consisting of two entangled photons is half the classical wavelength associated with either photon. Boto et al showed that the ability to write small structures scales with the order  $N$  of the interaction. That is, if  $N$  photons are entangled and the recording medium responds by  $N$ -photon absorption, features of size  $\lambda/(2N)$  can be written into the material.

In summary, quantum lithography holds great promise for the writing of sub-Rayleigh structures, and by extension to other sorts of sub-Rayleigh imaging. To date, no compelling demonstrations of quantum lithography have been presented, although proof-of-principle experiments that display certain aspects of quantum lithography have been presented. The selection of a highly sensitive recording material that functions by means of multiphoton absorption seems crucial to the success of the proposal of quantum lithography. It is hoped that with the development of new light sources and new lithographic materials it will be possible to implement true quantum lithography in the near future.

### **Quantum Optical Coherence Tomography (QOCT)**

This work was conducted by Bahaa Saleh, Alexander Sergienko, and Malvin Teich of Boston University. This group demonstrated axial Q-OCT imaging for multi-layered and scattering media. Dispersion cancellation has been demonstrated experimentally. In conjunction with this, a method for measuring the dispersion coefficient of the interstitial media between boundaries in the sample has been developed and validated. Resolution enhancement in the transverse direction has been concomitantly achieved with improved resolution in the axial direction by making the Q-OCT apparatus compact and by judiciously inserting optical elements that leave path indistinguishability in place to insure robust interference patterns. Three-dimensional images of a biological sample have been obtained in the form of A-, B-, and C-scans. A statistical analysis of Q-OCT measurement accuracy has been carried out. Novel periodically-poled, and chirped quasi-phase-matched (chirped-QPM), nonlinear-optical structures have been conceived, fabricated, and used to generate ultrabroadband SPDC and thereby to improve the resolution available in Q-OCT, as well as in OCT. Q-OCT resolution has been further enhanced, to a value of  $0.85 \mu\text{m}$ , by the use of superconducting single-photon

detectors (SSPDs). It has been shown that OCT resolution can be enhanced by manipulating the pump spatial distribution. A polarization-sensitive version of Q-OCT, known as PS-Q-OCT, has been analyzed and constructed, and its behavior has been shown to be in accord with theoretical predictions.

The use of chirped-QPM SPDC and SSPDs have also been shown to improve the resolution of photon-counting OCT centered at a wavelength of 1064 nm, which is suitable for achieving deep penetration of broadband optical radiation into biological tissue. Attention has been drawn to the principles of guided-wave SPDC, which can be used to increase photon flux and miniaturize the apparatus. Two data processing tools have been briefly examined: algorithms for image reconstruction in Q-OCT and compressed sensing in spectral-domain OCT. Quantum-mimetic optical coherence tomography (QM-OCT), in the form of phase-conjugate optical coherence tomography (PC-OCT) and chirped-pulse optical coherence tomography (CPOCT), have been shown to successfully mimic dispersion cancellation and other salutary features of Q-OCT. These implementations have the advantage that they make use of classical, rather than nonclassical, light. Various versions of QM-OCT also offer unique additional benefits, such as enhanced signal-to-noise ratio and acquisition rate.

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